1·

Isokinetic Sampling

The present invention relates to isokinetic
sampling. It is particularly, but not exclusively,
related to methods and apparatuses for carrying out
isokinetic sampling, and in particular isokinetic
sampling in oilfield applications.

In oilfield applications, as in many other fields,
it is important to be able to analyse the composition and
properties of a multi-phase fluid stream, such as a gas-
condensate stream or a wet-gas stream. In particular it
is desired to know the quantity of the various phases of
the flow, for example by knowing the gas-oil ratio (GOR)
or the condensate-gas ratio (CGR). It is also desired to
know the properties of the various phases, for example
their pressure, volume and temperature (PVT)
relationships.

For example, the prediction of fluid phase behavior
and reservoir simulation models based on equations-of-
state (EOS) typically requires high quality PVT data.

PVT data are also often needed for flow assurance in
wells and transport lines.

Furthermore, PVT data often have a significant
impact on processing facility designs and specifications,
and therefore on the profitability of gas-oil field.

However, to accurately determine the PVT properties
and composition of reservoir fluid, representative fluid
samples are required. Common analysis sampling procedures
suffer from deficiencies in either or both of their
accuracy and their ability to cope with high flow rates.

2

For example, a high-rate gas condensate well
producing 5-100 MMscf (Millions standard cubic feet)/day
with a gas-oil ratio of 3k-100k scf/bbl (CGR from 0 to
200 bbl/MMscf) (bbl = barrel of liquid; 1 m³ = 6.29 bbl),
5   can often overwhelm a test-separator, causing liquid
carry-over in the separator gas outlet line, thereby
providing poor measurement of the GOR and non-
representative PVT samples (if the carry-over is not
measured and corrected for). This normally also results.
10 in poor recombination ratios. Gas condensate wells are
particularly problematic for sampling as large volumes
of gas are associated with only small volumes of liquid,
and the phase behavior will be highly sensitive to the
quantity and composition of the liquid phase.
15   Wellhead sampling is therefore considered to be the
only practical method of obtaining reliable test data for
such applications. Isokinetic sampling at a wellhead of
a multiphase fluid is desirable since, if achieved, it
means that the sample of the fluid is at the same
20 pressure, temperature and velocity as the main flow
stream, and therefore will have identical properties to
that main flow stream.

A known wellhead sampling system is shown
25 schematically in Figure 1, which is taken from Dybdahl
and Hjermstad "A systematic approach to sampling during
well testing", Society of Petroleum Engineers (SPE) paper
69427, SPE Latin America & Caribbean Petroleum
Engineering Conference, Buenos, Argentina, 25-28 March
30 2001 (see also the paper by Henk et al. "Testing of gas
condensate reservoirs ᵣ sampling, test design and
analysis", SPE paper 68668, SPE Asia Pacific Oil & Gas

Conference, Jakarta, Indonesia, 17-19 April 2001). Such
a system is, for example, produced by Petrotech under
their IsoSplit(TM) wellhead sampling and separator
sampling services.

5   The wellhead sampling system of Figure 1 consists of
two parts.

The first part is a wellhead mixing/sampling
manifold 1010, which is positioned upstream of the choke
manifold 1030, and has a focusing-action static mixing
10   device 1015 (see GB 2301297 & US 5894080; a similar
mixing device is shown in Figure 2a) for collecting
liquid at the wall of the pipe and distributing it into
the main flow stream. A sampling probe 1020 is radially
inserted downstream of the mixer 1015 for withdrawing a
15   sample of the main flow stream.

The second part is an on-site laboratory 1050 (also
called a "Mini-lab"), which processes the sampled stream
to measure the condensate-gas ratio (CGR). PVT samples
for compositional characterization are taken.

20   As described in SPE paper 68668, the liquid
distribution across the flow pipe of Figure 1 will vary,
and either a mixing device or a traversing probe has to
be used in order to have a split stream sample with the
correct gas condensate ratio. As described in SPE paper
25   69427, the probe traversing enables sampling at multiple
points across the pipe and the subsequent correction for
the droplet and velocity distribution. It is stated in
SPE 68668 that the liquid collected from the wall by the
focusing-action mixer 1015 is distributed homogeneously
30   into the flowing gas stream. However, our own gas-liquid
ratio (GLR) profile measurement shown in Figure 2b, for a
mixer design (shown in Figure 2a) similar to the

4

focussing-action mixer 1015, indicates a liquid-rich jet
at the central region of the sampling cross section. The
GLR measured at such points will be a gross under-
estimate of the pipe average value. Figure 2b shows a -

5   70% error in the GLR at the pipe centre, with respect to
the pipe reference GLR.

      SPE paper 68668 also states that sample withdrawal
through the sampling probe 20 from the main stream is
performed at an isokinetic sampling rate, i.e. at the

10   same linear velocity as the wellhead fluid stream, which
is necessary to sample the gas and liquid phase in the
correct ratio. This isokinetic sampling rate is said to
be calculated from the probe size and the gas flow rate
measured at the test separator.

15   This approach has at least the following
disadvantages:

      1)   A test separator is needed for wellhead
               sampling operations, which is bulky and
               expensive (Figure 1).

20   2)   The test separator can be overwhelmed by
               high-rate gas wells, leading to liquid
               carry-over in the separator gas outlet line.
               This can result in an inaccurate main-stream
               gas rate measurement used to set the

25   isokinetic sampling rate.

      3)   The main-flow gas rate can fluctuate, for
               example due to changes in the liquid
               loading. This unsteadiness in the main flow
               rate can cause the separator gas rate

30   measurement to be unreliable (see SPE paper
               76766, by B.C. Theuveny and P. Mehdizadeh
               "Multiphase flowmeter application for well

5

and fiscal allocation", Alaska, 20-22 May 2002), leading to unreliable isokinetic sampling.

4)   Isokinetic sampling rate control based on measured main-stream <u>gas</u> flow rates can lead to errors when liquid loading becomes relatively high.

WO00/49370 describes a method for measuring the liquid and gas flow rates of a multi-phase fluid stream including withdrawing a portion of the overall flow rate under "isokinetic conditions". The sampled portion forms approximately 5% to 15% of the total flow rate.

The methods and apparatus disclosed in WO00/49370 do not independently measure the main flow stream, but instead derive measurements of the main flow stream from . the effect of the sampling operation on the flow stream. Furthermore, although the methods described are claimed to be "isokinetic", this term is applied to all sampling in which the ratio of the sampled flow rate to the calculated total flow rate is within 20% of the ratio of the cross sectional area of the sampling probe to the cross sectional area of the flow stream. Adjustment of the sampling conditions is only made if the ratio falls outside this range.

The method proposed in WO00/49370 for measuring the total flow rate (Q_1) of the fluid stream is given in equation (5) of that application, with Q_1 being calculated

as the sole unknown in the equation $\dfrac{\Delta p_1}{\Delta p_2} = \left(\dfrac{Q_1}{Q_1 - q}\right)^2$, where q

is the measured sampled flow rate and Δp_1 and Δp_2 are measured pressure differences of the main flow stream with and without sampling operating. This assumes that

the density of the sampled flow q is the same as the density of the total flow Q_1.

Thus Q_1 is calculated as $Q_1 = q \dfrac{\sqrt{\Delta p_1 / \Delta p_2}}{\sqrt{\Delta p_1 / \Delta p_2} - 1}$.   From this equation, the error δQ_1 in Q_1 can be determined as

$\left(\dfrac{\delta Q_1}{Q_1}\right)^2 = \left(\dfrac{\delta q}{q}\right)^2 + \left(\dfrac{\delta P}{P}\dfrac{1}{P-1}\right)^2$, where $P = \sqrt{\Delta p_1 / \Delta p_2}$.   For $P \gg 1$,

$\dfrac{\delta Q_1}{Q_1} \approx \dfrac{\delta q}{q}$.   However, as $\sqrt{\Delta p_1 / \Delta p_2} \to 1$, $\dfrac{\delta Q_1}{Q_1} \to \infty$.   Therefore, in order to avoid excessive errors in the measurement of the total flow rate Q_1 when using the method of WO00/49370 it is important that the difference between Δp_1 and Δp_2 is large, and consequently that the flow rate of the sampled flow is a substantial proportion (i.e. more than 5%) of the total flow rate. When such sampling proportions are used in high flow situations, for example in a high-rate gas condensate wells, they can overwhelm the separator, or alternatively require a larger, and therefore more expensive separator.

The present invention is at least partly based on the realisation that isokinetic sampling from a fluid stream can be achieved by monitoring the ratio of the flow rate of the sampled flow to the total flow rate of the main fluid stream and adjusting the sampling rate accordingly. Contrast this with WO00/49370 which provides no suggestion that any repeated or continuous adjustment to achieve isokinetic sampling should be carried out, and indeed assume that sampling is carried out under isokinetic conditions in order to measure the total flow rate.

Thus, a first aspect of the present invention
provides a method of sampling a multi-phase fluid stream
comprising the steps of:

    sampling, with a sampling probe, a portion of the
5 fluid stream;

    measuring the flow rate Q_s of said sampled portion;
and

    measuring, independently of the sampling step, the
total flow rate Q of the fluid stream,

10   wherein the flow rate of the sampled portion is
controlled according to the ratio of the flow rate of the
sampled portion to the flow rate of the fluid stream, in
order to obtain substantially isokinetic sampling of the
fluid stream.

15   Preferably the flow rate of the sampled portion is

controlled such that the equation $\dfrac{Q_s}{Q} = \dfrac{A_{probe}}{A_{pipe}}$ is satisfied

to within 10%, more preferably to within 5%, where A_{probe}
and A_{pipe} are the respective cross-sectional areas of the
sampling probe opening and the fluid stream at the
20 sampling point.

    The flow rates Q and Q_s may be mass flow rates, and
the flow rate Q_s of the sampled portion of the fluid
stream is preferably less than 0.2% of the total flow
rate Q, more preferably less than 0.05% of the total flow
25 rate Q.

    The method may be used in high-rate gas condensate
wells, where the gas flow rate is at least 5 MMscf/day.
In wells with higher flow rates, the flow rate of the
sampled portion of the fluid stream is particularly
30 preferred to be a small proportion of the total flow rate
so that downstream analytical processes on the sampled

portion are not overwhelmed. An advantage of the present invention is that it can be used to sample relatively small proportions of the total flow.

Preferably the method further includes the step of separating said sampled portion into a sampled liquid flow and a sampled gas flow, and said step of measuring the sampled flow rate includes measuring the flow rate of the sampled liquid flow and the flow rate of the sampled gas flow. Either or both of these sampling flows may be measured using a Coriolis flow meter. This allows more accurate measurement of the flow rates of the different phases of the fluid stream. A Coriolis flow meter also allows the density of the flow to be measured.

In certain embodiments the step of measuring the total flow rate includes measuring the density of the fluid stream. The step of measuring the total flow rate may include measuring a differential pressure, which may, for example, be measured using a Venturi meter, or be an impact pressure measured using a Pitot tube.

Preferably the step of measuring the total flow rate is carried out continuously or repeatedly during the sampling process.

Preferably the step of controlling the flow rate of the sampled portion is carried out continuously or repeatedly during the sampling process.

The continuous or repetitive measuring of the total flow rate and controlling of the flow rate of the sampled portion allows correction of the flow rate of sampled portion in response to changes in the mass flow rate of the main flow stream.

In this respect, the term "continuous" also includes repeated discrete applications of the measuring and

controlling steps above at regular intervals, these
intervals being shorter than the time scale over which
significant changes in the total mass flow rate of the
main stream occur.

5   The above method is particularly applicable where
the fluid stream is a feed from a well-head, and may be
carried out at a well-head site.

        Preferably the method further includes, prior to
sampling the fluid stream, the step of conditioning the
10   fluid stream.

        Another aspect of the present invention provides a
sampling apparatus for a multiphase fluid stream which
can carry out the method of the above aspect.

15   According to this aspect, the present invention
provides a sampling apparatus for sampling a multi-phase
fluid stream, comprising:

        means for measuring the total flow rate Q of the
fluid stream;

20   a sampling probe for sampling a portion of said
fluid stream;

        a meter for measuring the flow rate Q_s of said
sampled portion; and

        a controller adapted to control the flow rate of the
25   sampled portion according to the ratio of the flow rate
of the sampled portion to the total flow rate of the
fluid stream, in order to obtain substantially isokinetic
sampling of the fluid stream.

        Preferably the controller is adapted to control the
30   flow rate of the sampled portion such that the equation

$\dfrac{Q_s}{Q} = \dfrac{A_{probe}}{A_{pipe}}$ is satisfied to within 10%, more preferably to

within 5%, where A_{probe} and A_{pipe} are the respective cross-sectional areas of the sampling probe opening and the fluid stream at the sampling point.

Flow rates Q and Q_S may be mass flow rates, in which case the meter is a mass flow rate meter.

Preferably the cross-sectional area of the sampling probe opening is less than 0.2% of the cross-sectional area of the fluid stream at the sampling point, and thus the flow rate of the sampled portion is a similar fraction of the total flow rate of the fluid stream. More preferably the cross-sectional area of the sampling probe opening is less than 0.05% of the cross-sectional area of the fluid stream at the sampling point.

The sampling apparatus may form part of a high-rate gas condensate well wherein the gas flow rate is at least 5 MMscf/day.

Preferably the apparatus further includes a separator for separating the sampled portion into a sampled liquid flow and a sampled gas flow; a meter for measuring the flow rate of the sampled liquid flow; and a meter for measuring the flow rate of the sampled gas flow. Either or both of these meters may be Coriolis flow meters.

In some embodiments the means for measuring the total flow rate may include a densitometer for measuring the density of the fluid stream. The means for measuring the total flow rate may additionally or alternatively include a differential pressure sensor, such as that for use with a Venturi meter or a Pitot tube.

Preferably the means for measuring the total flow rate operates continuously or repeatedly during the sampling process.

Preferably the controller controls the flow rate of the sampled portion continuously or repeatedly during the sampling process.

Preferably the sampling probe is made from damage resistant material such as tungsten carbide or cobalt alloy, so that the cross sectional area of the sampling probe opening does not vary during the sampling process.

The sampling probe is preferably located in the centre of the pipe section.

Preferably the sampling apparatus further includes a flow conditioner located upstream of the sampling probe.

The fluid stream may be a feed from a well-head.

In order to achieve representative isokinetic sampling of a multi-phase stream using sampling at a single sampling point, it is preferable that, at the designated sampling cross-section of the pipe, the cross-pipe GLR profile is uniform.

Previously flow-focussing mixers have been used to try to provide such a uniform GLR profile. Examples of such mixers are plug-valve mixers, for example as shown in GB 2301297 and US 5894080. A similar mixer to that in GB 2301297 is shown schematically in Figure 2a. Where similar reference numerals are used in Figure 2a, they refer to features already described in association with Figure 1.

However, use of flow-focussing mixers, such as the mixer 1015 shown in Figure 2b, can result in too much liquid being entrained into the central pipe region as a result of the focussing action of the mixers. At low pressures there may be excessive liquid jetting, leading to very non-uniform cross-pipe GLR and a large GLR error.

12

Figure 2b shows the GLR cross-pipe profile for air/water flows with an equivalent CGR of ~60 bbl/MMscf gas (gas rate $q_g \approx 1400$ m³/h or about 1.2 MMscf/day), and shows that the measured GLR has an error of approximately -70%

5   from the reference value at the pipe centre.

It is anticipated that as the wellhead pressure increases, the GLR cross-pipe non-uniformity will improve as a results of the reduction in the gas-liquid density contrast, and hence in the gas-liquid velocity slip.

10   However, the adverse effect of liquid jetting will still remain, even at high wellhead pressures. Similar results are expected to be seen with the plug-valve type mixers referred to above.

15   Therefore a further aspect of the present invention provides a flow conditioner for a wellhead sampling system, the flow conditioner being a pipe section including: a swirl inducing section; a flow straightener; and an orifice plate.

20   To achieve accurate isokinetic sampling at wellhead at a single sampling point, it is preferable to have a uniform cross-pipe GLR profile at the designated sampling cross-section. For annular or annular-mist flows prevailing in a wellhead sampling system (i.e. not fully

25   developed vertical upward or downward flow), this can be achieved by removing liquid film from the pipe wall and by entraining it homogeneously in the gas core. It is also preferable that liquid drop re-deposition onto the pipe wall should be negligible at the sampling cross-

30   section. Drop size is preferably small thereby minimizing gas-drop velocity slip and the rate of drop deposition. These factors will lead to a more

representative sampling of gas and liquid flow rates, and
hence a better measure of the GLR.

The creation of the initial swirl, upstream of the
orifice plate, preferably creates a uniformly
5 circumferentially distributed liquid film on the wall of
the pipe section. The orifice plate sheds any such
liquid film on the pipe wall back into the gas flow.
After the initial formation of a liquid rich core
downstream of the orifice plate, turbulence causes good
10 mixing of the liquid and gas phases. Straightening the
flow of the gas core prior to the orifice plate reduces
the amount of liquid that is redeposited onto the pipe
wall after shedding by the orifice plate. Therefore a
relatively uniform cross-pipe GLR can be achieved, making
15 it less important where on the pipe diameter in the
sampling cross section a sampling probe is placed.

The swirl inducing section may include a tangential
input to the pipe section. Alternatively the swirl
inducing section may include a helical insert inside the
20 pipe section.

The flow straightener is preferably located in the
centre of the pipe section and such that there is an
annular gap between the flow straightener and the wall of
the pipe section, thereby straightening the gas core of
25 the fluid stream whilst not affecting any liquid film
located on the wall of the pipe.

The orifice plate may have a diameter of its open
section which is between 0.85 and 0.95 of the local
diameter of the pipe section, preferably between 0.9 and
30 0.95 of the local diameter of the pipe section (also
referred to as the diameter ratio β).

14

The pipe section may narrowed at the orifice plate. The narrowed pipe section gives a higher gas flow momentum and higher gas Weber number.

To improve CGR measurement accuracy of lean gas condensate wells (CGR = 0 to 50 bbl/MMscf), a dual-orifice mixer arrangement is preferably used for reducing liquid rate under-sampling at low liquid loadings.

In one example of such an arrangement, the first (i.e. upstream) orifice plate has a diameter ratio such as $\beta_1=0.9$, and the second orifice plate has a diameter ratio such as $\beta_2=0.95$. The two orifice plates may be axially separated by 1D to 3D, where D is the basic diameter of the pipe at the orifice plates.

The first, upstream orifice plate (diameter ratio β_1) is intended to shed as much as liquid to the pipe centre as possible (with a relatively small β-ratio); whilst the second orifice plate is used to shed any relatively thin liquid film that might be caused by the re-deposition of the liquid drops shed by the first orifice plate, after travelling a few pipe diameters.

A sampling probe may be used to sample the fluid stream, and is preferably located downstream of the orifice plate(s). More preferably the sampling probe is located at a distance between 1D and 3D downstream of the downstream orifice plate, where D is the diameter of the pipe section at the orifice plate (not the diameter of the orifice plate itself).

Preferably the sampling probe is located in the centre of the pipe section.

Another aspect of the present invention provides a method for conditioning the flow of a multi-phase stream comprising the steps of successively:

forming a liquid film at the wall of a pipe section
5   which carries the fluid stream;

straightening the flow of at least a core of the fluid stream; and

shedding the liquid film into said core.

Preferably the liquid film is substantially
10   uniformly circumferentially distributed on the pipe wall.

The step of shedding the liquid film may use at least one orifice plate. The or each orifice plate may have an open diameter of 0.85 to 0.95 of the diameter of the pipe section in which it is placed, preferably
15   between 0.9 and 0.95 of the diameter of the pipe section. The pipe section may narrow at at least the orifice plate.

The step of forming the liquid film may include causing the fluid stream to swirl about the axis of the
20   pipe section. Such rotary motion may be achieved by, for example, tangentially introducing the fluid stream to the pipe section, or by passing the fluid stream through a helical insert inside the pipe section.

Preferably the step of straightening the core of the
25   fluid stream does not straighten a portion of the fluid stream adjacent to the walls of the pipe, and therefore does not affect the liquid film.

The fluid stream may be sampled using a sampling probe, the sampling preferably taking place downstream of
30   the orifice plate(s). More preferably the sampling probe is located at a distance between 1D and 3D downstream of the downstream orifice plate, where D is the diameter of

the pipe section at the orifice plate (not the diameter of the orifice plate itself).

Preferably the sampling probe is located in the centre of the pipe section.

The flow conditioner or method of the above two aspects may be used with the sampling methods and apparatuses of the earlier aspects to improve the accuracy of the isokinetic sampling.

Embodiments of the present invention will now be described in relation to the accompanying drawings, in which:

Figure 1 is a schematic illustration of a known wellhead sampling system, and has already been described;

Figure 2a is a schematic illustration of a flow-focusing mixer similar to that shown in GB 2301297 the prior art and has already been described;

Figure 2b shows the GLR cross-pipe profiles downstream of the mixer of Figure 2a and downstream of a flow conditioner according to an embodiment of the present invention;

Figure 3 is a flow chart showing a method according to an embodiment of the present invention;

Figure 4 is a schematic illustration of an isokinetic sampling system according to an embodiment of the present invention;

Figure 5 is a schematic illustration of an isokinetic sampling system according to another embodiment of the present invention;

Figure 6 is a schematic illustration of an isokinetic sampling system according to a further embodiment of the present invention;

Figure 7 is a schematic diagram of a flow
conditioner according to an embodiment of the invention;

Figure 8 is a schematic diagram of a flow
conditioner according to an alternative embodiment of the
5   invention; and

Figure 9 is a schematic diagram of a flow
straightener which may be used in the flow conditioners
shown in Figures 7 and 8.

10   Elements of a method of sampling according to an
embodiment of the present invention are shown in the flow
chart of Figure 3.

A portion of a fluid stream is sampled, and the flow
rate Q_s of that sampled portion measured. The total flow
15   rate Q of the fluid stream is also independently·
measured, and the ratio of the two measured flow rates
calculated. Based on this ratio, the sampling flow rate
(i.e. the proportion of the fluid stream which is
sampled) is adjusted in order to substantially obtain
20   isokinetic sampling conditions. This process is
preferably either repeated or carried out continuously
throughout the sampling process.

The sampled portion may be analysed concurrently
with the flow rate measurements and adjustments, for
25   example to provide the GOR, the WLR and samples for PVT
analysis. This analysis may also use the flow rate
measurement of the sampled portion.

Figure 4 shows an isokinetic sampling system
30   according to an embodiment of the present invention.

An isokinetic sampling model is used to calculate
the target sampling flow rate Q_{so}, according to the main

18

stream flow rate Q_{eff}. One example of such an isokinetic

sampling model is $\dfrac{Q_{So}}{Qeff} = \dfrac{A_{probe}}{A_{pipe}}$ for substantially uniform

mixed flow.

In contrast to the method described in relation to
5   Figure 1 above, in the present embodiment, the main
stream flow rate Q_{eff} is measured on-line in the pipe by a
main pipe flow meter 40. This may be, for example, a
Venturi or an orifice meter. The measured Q_{eff} is then
fed into the sampling model so that Q_{so} is updated as Q_{eff}
10 varies.

When the on/off valve 35, allowing sampling to take
place, the actual sampling flow rate Q_s is measured by a
sampling flow meter 30 positioned in the sampling line.
The actual sampling flow rate Q_s and the target sampling
15 flow rate Q_{so} are compared in comparator 33, which creates
a flow control signal 31, on the basis of which control
valve 32 is adjusted by the actuator 34 so as to keep Q_s =
Q_{so}.

Alternatively flow control signal 31 may be created
20 as a result of a direct comparison between the main
stream flow rate Q_{eff} measured by the main pipe flow meter
40 and the sampling flow rate Q_s measured by the sampling
flow meter.

The main pipe flow meter 40 of the embodiment of
25 Figure 4 may be positioned upstream or downstream of a
mixer or other flow conditioner (not shown). In certain
embodiments, the main pipe flow meter will also serve as
a good gas-liquid mixer, and so a separate flow
conditioner may not be required.

30 However, use of a flow conditioner upstream of a
flow meter 40 can serve to eliminate or substantially

reduce the gas-liquid velocity slippage for the flow
passing through the main pipe flow meter 40, thereby
allowing a homogenous flow model (e.g. standard single-
phase Venturi equations) rather than a slip-model (e.g. a
5   2-layer, separated model for annular or annular-mist
flows) to be used to calculate the main stream flow rate.
The homogenous mixing state is assumed to be maintained
over some distance downstream of the main pipe flow meter
40, enabling the sampling probe to perform the desired
10   isokinetic sampling.

Preferred embodiments of separate mixers or flow
conditioners are described below.

Another embodiment of the present invention is shown
15   schematically in Figure 5. An embodiment of the method
of the present invention is also described in relation to
this Figure. Again components which have already been
discussed in relation to Figures 1 and 4 have the same
reference numbers.

20   This embodiment has a flow meter 40 which combines a
Venturi pressure drop measurement 41 with a gamma-ray
densitometer 42. An example of such a meter is the
PhaseTester/PhaseWatcher(TM) Vx Venturi meter described
in SPE paper 77405 (by S. Jayawardane and B.C. Theuveny
25   "PVT Sampling With Multiphase Flowmeters-Theoretical
Justifications and Field Limitations", SPE Annual
Technical Conference & Exhibition, San Antonio, Texas, 29
September to 2 October 2002). The pressure and
temperature (p, T) of main flow stream 11 can also be
30   measured at this point. The Vx flow meter has been shown
(see SPE paper 76766) to give better multiphase flow rate

20

measurement than a test separator, especially at high gas rate and/or unsteady flow conditions.

This embodiment uses a total mass flow rate measurement $Q = K\sqrt{\Delta p.\rho_H}$, obtained from the combined measurements of high-energy mixture density (ρ_H, calculated to about 10 kg/m^3 accuracy by the Vx nuclear source) and Δp from the Venturi measurement (calculated to within 1% accuracy) to set the extraction rate for isokinetic sampling, where K is a calibration factor depending on Venturi throat diameter, inlet diameter and the discharge coefficient; see, for example, eq.5 in SPE paper 77405. The mass flow rate error $\dfrac{\Delta Q}{Q} = \dfrac{1}{2}\left[\dfrac{\Delta(\Delta p)}{\Delta p} + \dfrac{\Delta\rho_H}{\rho_H}\right]$

is thus within 2.5% for a mixture density ρ_H = 300 kg/m^3.

The sampling probe 20 has an opening area (A$_{probe}$), or ratio of its area to the pipe area (A$_{pipe}$), which is known accurately to within 2% and is maintained unchanged over a long period. To achieve this, the probe tip 18 is made from damage-resistant material such as tungsten carbide or cobalt alloy.

Consideration is also given to the size of the opening of the sampling probe tip 18. In order to keep the relative error in the area of the opening of the probe, or in the area ratio to within 2%, a 1% accuracy is required in the diameter of the opening of sampling probe 20. Therefore for a small opening diameter sampling probe 20 (e.g. 1.5 mm), the tolerance in diameter has to be very high (< 15 μm). Increasing the opening diameter of the sampling probe 20, for example to 3 mm, reduces the demand on the machining tolerance for the probe (to < 30 μm for the 3 mm example above). For high GLR flows, a larger probe size may also be

beneficial as it will increase the amount of liquid sampled and therefore ease the sizing of the Coriolis mass flow meters 30a and 30b for use at higher ranges of gas and liquid flow rates in the mini-separator 50.

5   It is preferable to have a uniformly mixed wet-gas flow at the sampling cross section. This is achieved by placing a flow conditioner 200 upstream of sampling probe 20. Preferred embodiments of the flow conditioner 200 are described below.

10   It is also preferable that the stream at the Venturi portion of the Vx flow meter 40 is also homogenous wet-gas flow (i.e. with negligible gas-liquid slip), and so a further flow conditioner may be provided upstream of the Vx flow meter 40.

15   With the on/off valve 35 open and operating in conditions of well-mixed wet-gas flows in which there is low liquid mass (i.e. $Q_L/Q_G < 1$) the total mass flow rate measurement Q from the Vx flow meter 40

($Q = K\sqrt{\Delta p.\rho_H} = Q_G + Q_L = Q_G(1 + Q_L/Q_G)$) is first used to set an

20   approximate 'dry' gas sample extraction mass flow rate $Q_{S,G_0} = (A_{probe}/A_{pipe}) \times Q$ by adjusting flow control valve 32 in the mini-separator 50 through use of the actuator 34.

       The mass flow rate of the 'dry' gas sample flow $Q_{S,G}$, after gas-droplet separation in the gas-drop separator

25   51, can be directly measured using a Coriolis flow meter 30a.

       The sampled liquid mass flow rate $Q_{S,L}$ is measured using an instrumented liquid collection system 52 in the mini-separator 50. Precise achievement of isokinetic

30   sampling has less effect on the sample liquid mass flow

rate $Q_{S,L}$ than on the sample gas flow rate because of the higher inertia of liquid droplets compared to the gas.

In the mini-separator 50 the sampled liquid mass flow rate $Q_{S,L}$ can be derived from the change in the liquid level over time $h(t)$ in the liquid collection vessel 52 from a Dp level sensor (not shown) ($p = \rho_{S,L} g h; Q_{S,L} = (A_L / g)(dp/dt)$), where A_L is the cross-sectional area of the liquid collection vessel 52).

However, in the embodiment illustrated in Figure 5, $Q_{S,L}$ is also measured using a second Coriolis mass flow meter 30b, which also gives the liquid mixture density $\rho_{S,L}$. For example the second Coriolis mass flow meter 30b may be a Promass 80A™ Coriolis meter as made by Endress-Hauser. This meter can measure liquid mass flowrate to ±0.1%, gas mass flowrate to ±0.5% and density to ±1 kg/m^3, and is reported to measure flow rates as small as 0.1 kg/h.

An extra linear array of MEMS (Micro Electro Mechanical Systems) densitometer can be installed along the height of the liquid collection vessel 52, allowing oil and water densities ($\rho_{S,o}$, $\rho_{S,w}$) to be determined from the separated oil-water interface profile at separator temperature and pressure (T_S, p_S).

It is preferable that the liquid is separated at line pressure not following a pressure reduction to minimize mass transfer between the phases. It is also preferable that the liquid sample mass flow rate measurement system, whether it is a Coriolis meter or a measurement bottle has an error of 2% or less to achieve good results in the closed-loop feedback system described below (a better than 2% accuracy is necessary to obtain

23

an accurate measurement of the sampled liquid flow rate

$Q_{S,L}$, and of the main-pipe liquid rate $Q_L = (A_{pipe} / A_{probe}) \times Q_{S,L})$.

The water cut (γ_w) can then be determined from the liquid mixture density relation $\rho_{S,L} = \gamma_w \rho_{S,w} + (1 - \gamma_w) \rho_{S,o}$.

5   Alternatively the water cut can be measured by other means, for example using microwave or optical sensors, such as the RedEye™ infrared water-cut meter from eProduction Solutions, Texas US, prior to complete separation of the liquids.

10   The first measure of the liquid sample mass flow rate $Q_{S,L}$ is then combined with the measured sample gas mass flow rate in the controller 60 to obtain the total sample mass flow rate Q_S. The controller 60 then compares this with the current main pipe total mass flow

15   rate as measured by the main pipe flow meter 40. The sample extraction rate 19 is then varied as necessary by adjusting the flow control valve 32 in the mini-separator 50, through use of the actuator 34, so as to cause the sample mass flow rate to approach $(A_{probe} / A_{pipe}) \times Q$, and thus

20   isokinetic sampling conditions.

The above process can then be repeated for successive measurements of the total sample mass flow rate, thereby achieving convergence with the isokinetic sampling conditions. The process may be run effectively

25   continuously throughout the sampling process, and thereby adjust the sampling flow rate as necessary when the flow of the main stream varies for any reason. In this respect, the term "continuous" includes repeated discrete applications of the measuring and correcting steps above

30   at regular intervals, these intervals being shorter than the time scale over which significant changes in the

24

total mass flow rate of the main stream occur. A typical interval is less than 30 sec, and preferably less than 10 or 5 sec.

For the maintenance of isokinetic sampling in this system, the existence of a pressure difference between the main pipe 220 and the mini-separator 50 does not affect the sampling. Mass transfer between the liquid and gas phases can occur without prejudicing the sampling control process since the process is based on total mass flows and not on the volume rate of a single phase.

However, it is preferable that the pressures in the mini-separator 50 and in the main pipe 220 are approximately equal, so that no mass transfers between the gas and liquid phases occur between the pipe and the separator. In this situation, the main pipe gas and liquid mass flow rates can be obtained as follows:

Total mass flow rate $Q = K\sqrt{\Delta p \cdot \rho_H}$, obtained from the Vx Venturi Δp measurement and the high-energy mixture density ρ_H measurement;

Liquid mass flow rate $Q_L = \left(A_{pipe} / A_{probe}\right) \times Q_{S,L}$, obtained from the isokinetic sampling;

Gas mass flow rate $Q_G = Q - Q_L = Q - \left(A_{pipe} / A_{probe}\right) \times Q_{S,L}$, preferably obtained from the Vx total flow measurement and isokinetic sampling, also obtainable purely from the isokinetic sampling as $Q_G = \left(A_{pipe} / A_{probe}\right) \times Q_{S,G}$, which can therefore be used as a quality control check.

As a result, the PVT relations are no longer required to convert the liquid mass flow rate measured at separator conditions (p_S, T_S) to that at main stream conditions (p, T) in order to obtain gas and liquid mass flow rates from the Vx measurements and interpretation

models. However, PVT relations are required to convert the mass flow rates at line conditions (*p*, *T*) to volume flow rates at standard conditions.

The mini-separator 50 also provides the following
5   measurements of the sampled flow:

Densities $\rho_{s,G}$, $\rho_{s,L}$, $\rho_{s,o}$, $\rho_{s,w}$ (of gas, liquid, oil and water samples respectively) obtained from the Coriolis gas and liquid flow meters 30a and 30b and the MEMS densitometer array reading from the liquid
10   collection vessel 52;

Water cut $\gamma_w = (\rho_{s,L} - \rho_{s,o})/(\rho_{s,w} - \rho_{s,o})$ calculated from the densities above;

GLR $= (Q_{s,G}/\rho_{s,G})/(Q_{s,L}/\rho_{s,L})$ calculated from the separator gas and liquid volume flow rates;

15   Liquid mass loading $m = Q_{s,L}/Q_{s,G}$ calculated from the separator flow rates – ideally $m < 1$ for a well mixed wet-gas regime which the system is being used to analyse; and

PVT data from the samples obtained from the
20   separated liquid flow and separated (i.e. 'dry') gas flow in the mini-separator 50.

Another embodiment of the apparatus and method of the present invention is illustrated schematically in and
25   with reference to Figure 6.

As with the embodiments described above, it is preferable that the wet-gas flow at the sampling cross-section is well-mixed, and this is achieved using mixer or flow conditioner 200 positioned upstream of the
30   sampling cross-section. Again, preferred embodiments of the flow conditioner are described below.

An averaging Pitot-tube (APT) 44 is used to derive
the main pipe total mass flow rate when operating at
impact-pressure measuring (Pitot) mode, as well as as a
sampling probe. The APT 44 has multiple holes, for

5   example four or six holes, specifically arranged along
the diametrically aligned tubing. For example, for a
six-hole probe the holes are preferably placed on the
probe tubing at the following positions: -.913R, -.707R,
-.408R, +.408R, +.707R, +.913R, where R is the radius of

10 the pipe. The hole positions preferably correspond to
the centres of the sampled equal area annuli of the pipe
circular cross section. As with the previous embodiment,
for sampling accuracy it is preferable that the area of
the hole openings of the APT 44 ($A_{probe} = N_{hole} \times A_{hole}$),

15 relative to the pipe area A_{pipe} at the sampling cross-
section, is known to within 2% and does not change over
the time of testing and sampling. This can be achieved
by making the APT 44 from damage resistant material such
as tungsten carbide or cobalt alloy.

20   One example of an APT is the Rosemount Probar™
insertion meter operating at impact-pressure measuring
(Pitot) mode only, which claims a relative accuracy of
±1.1% in volumetric flow rate measurements for steam,
liquid and gas. APTs can also be obtained from

25 Thermocouple Instruments Ltd. Of Cardiff, UK.

An APT probe has very low pressure loss and
generally costs less than a Venturi flow meter. The pipe
averaging characteristics of the APT 44 reduce any
variations in the cross-pipe flow at the sampling cross

30 section.

A high energy gamma-ray densitometer 43 is installed
upstream of the APT probe 44 and downstream of the flow

27

conditioner 200 to obtain the density ρ_H. The
densitometer 43 can have an accuracy within 10 kg/m^3 from
a 30 mCi ^{137}Cs source (with high energy gamma-ray at
661.66 KeV) and a NaI scintillation detector.

5   The APT 44 is first set to operate in normal impact
pressure measurement mode, with on/off valve 35 set in
the off position and with no sampling flow being taken.
The APT measures the differential pressure Δp across the
main-pipe static pressure tap and the APT probe static

10   pressure tap (typically to within 1% accuracy), and the
main pipe total mass flow rate is calculated as

$Q = K_1\sqrt{\Delta p.\rho_H}$ (here K_1 is a calibration factor dependent on
the probe geometry and flow Reynolds number).

        The APT 44 is then switched to operate in sampling

15   mode by opening the on/off valve 35 and by adjusting flow
control valve 32 through actuator 34. The averaging
nature of the APT 44 means that the main flow stream is
sampled at multiple points across the diameter of the
sampling cross section. Therefore variations in the

20   cross-pipe GLR profile, which may be found downstream of
an imperfect flow conditioner, can be largely overcome.
Alternatively, when an APT is used, as in the current
embodiment, the performance requirements of the flow
conditioner can be made less stringent.

25   Operating in conditions of wet-gas flows in which
there is low liquid mass (i.e. $Q_L/Q_G < 1$) the total mass
flow rate measurement Q from the gamma-ray densitometer
43 and the APT 44 operating in impact pressure
measurement mode ($Q = K_1\sqrt{\Delta p.\rho_H} = Q_G + Q_L = Q_G(1 + Q_L/Q_G)$) is

30   first used to set an approximate 'dry' gas sample

28

extraction mass flow rate $Q_{S,G_a} = \left(A_{probe}/A_{pipe}\right) \times Q$ by adjusting

flow control valve 32 in the mini-separator 50.

The remainder of the sampling process is the same as

that described in relation to Figure 5 above. In

5   particular the flow control valve 32 is adjusted via the

actuator 34 so that the sampling flow 19 is substantially

isokinetic with the main pipe flow stream 11.

In a further embodiment, a single-hole sampling

probe 20, such as that used in the embodiment described

10 in relation to Figure 5 above, can also be set to operate

in impact pressure mode by switching valve 35 off and

measuring the differential pressure Δp across a main pipe

static pressure tap and a static pressure tap on the

probe 20. This measurement of Δp could then be used to

15. derive an independent estimate of the main pipe total

flow rate using the density ρ_H measured by densitometer

42.

In a further embodiment, in applications where the

probe pressure loss (i.e. from the probe opening to the

20 probe pressure tap) is relatively small, the isokinetic

sampling condition can be substantially achieved by

nulling the Δp described above by adjusting the sampled

flow rate of the sampled portion through the use of flow

control valve 32. In this embodiment, the Δp signal can

25 be used as a control signal to control actuator 34, thus

avoiding the use of flow meters 30a and 30b. Note that

this embodiment can be adapted to either the single hole

probe shown in Figure 5 or the multiple hole pitot tube

probe shown in Figure 6.

30 Note that the multiple-hole pitot tube sampling

embodiments described in connection with Figure 6 can

also be used in applications where the independent

measurement is made using Vx type meters as described in connection with Figure 5.

Figure 7 is a diagram of a pipe section which is arranged to provide a relatively uniform cross-pipe
5   profile at the sampling cross-section, particularly with regard to the GLR. The pipe section shown has a flow conditioner 200 for providing such a cross-section.

The flow conditioner 200 has three elements: a swirl inducing portion, which is provided in this embodiment by
10   the tangential flow input 201; a gas flow core straightener 202; and an orifice plate 203.

The tangential flow input 201 causes the entire flow to swirl, thereby creating a substantially uniformly circumferentially distributed liquid film on the pipe
15   wall 205. This removes variations due to the inflow conditions, such as non-axisymmetric gas and liquid flow distributions.

The core of the flow, which is mostly gas, is then straightened by the core straightener 202 positioned
20   downstream of the tangential input 201. An example of such a core straightener 202 is illustrated in Figure 9 and comprises a conventional straightener 212 (such as those described in US 3840051, US 5309946 and US 5762107) positioned with an annular gap 213 between the
25   straightener 212 and the pipe wall 205 so as not to interfere with the liquid flow along the pipe wall. The core straightener 202 removes the swirl in the central gas core of the flow, thereby reducing the amount of liquid re-deposited on the wall after the orifice plate
30   mixing. This facilitates the obtaining of consistent gas-liquid flux profiles at the sampling cross-section.

Downstream of the core straightener 202, an orifice
plate 203 is positioned, which causes the liquid film
flowing on the pipe wall to be shed back into the now
straightened gas core. The diameter β-ratio (the ratio
of the open diameter of the orifice plate 203 to the
diameter of the pipe) is preferably between 0.85 and
0.95. A further orifice plate (not shown) may be
positioned downstream of orifice plate 203, and sheds any
liquid film re-deposited on the wall after the orifice
plate 203.

The liquid shed from the pipe wall by the orifice
plate 203 is then subjected to an acceleration-induced
catastrophic break-up by the gas flow which has a high
axial velocity. In the region immediately downstream of
the orifice plate 203, a liquid rich cone is formed at
the centre of the flow. Downstream of this cone, the
turbulent kinetic energy is high and hence the secondary
turbulent break-up controls the droplet size
distribution. Further downstream, as the turbulent
kinetic energy decays quickly, turbulent break-up ends
and coalescence effects determine the liquid droplet
size. Thus the cross-pipe liquid flux distribution
downstream of the orifice plate 203 is totally different
from that upstream of the plate 203.

The sampling probe is preferably placed at an axial
distance L downstream of the orifice plate 203, the
distance L being chosen so as to avoid sampling at the
liquid-rich core region caused by the shedding of the
liquid film by the orifice plate 203, and to allow for
some break-up due to turbulence and diffusion, leading to
smaller drop sizes and more uniform cross-pipe GLR. The
preferred values of L are 1D to 3D.

The use of an orifice-plate type mixer 203 is
preferable to the flow-focusing type mixers, such as
those disclosed in GB 2301297 and US 5894080. An easy-
to-machine orifice-plate mixer 203 serves to shed the
liquid film from the pipe wall, which is then subjected
to acceleration-induced catastrophic break-up by the
incoming high axial-velocity gas flow. For a 4" pipe
diameter (D = 100 mm) down-flow example at low pressures,
a much more uniform cross-pipe GLR has been
experimentally measured 3D downstream of a single
orifice-plate 203 with diameter ratio $\beta = 0.95$ (see Figure
2b) than that obtained with the flow-focusing mixer 15
shown in Figure 2a (which is similar to that described in
GB 2301297). As a result, the GLR error at the pipe
centre is reduced by about five-fold over the flow-
focusing type mixer shown in Figure 2a. The orifice
plate and the flow-focusing mixer were both tested at the
same CGR of 60 bbl/MMscf, at a gas rate of 1.2 MMscf/day.

The embodiment of Figure 7 shows the flow
conditioner and sampling probe 20 implemented in a pipe
section 210 of smaller diameter than the main pipe 220
(for example a section of 2 inch (D = 50 mm) rather than
4 inch (100 mm) diameter). For a given mass flow rate of
a well stream, deploying the sampling probe 20 at a small
diameter pipe section 210 achieves the highest gas flow
momentum $(\rho_G U_G^2)$ and hence the highest gas Weber number
$We_D = \rho_G U_G^2 D / \sigma$ (where σ is the surface tension). This may
be beneficial as it: increases the shear for the liquid-
film primary break-up from the wall, hence increasing
drop formation; causes generation of small size droplets,
thereby reducing the drop Stokes number and gas-drop

velocity slip; increases the cross-pipe uniformity and
the percentage of liquid entrainment.

An alternative embodiment of the flow conditioner
200 is shown in Figure 8. This embodiment is the same as
that in Figure 6, except that the tangential input 201
has been replaced by a bend inlet 221 followed by a
helical insert 211 to provide the initial swirl.

Alternative embodiments which cause axisymmetric
distribution of the liquid film on the pipe wall, by
causing swirl in other ways may also be used.

The above embodiments may form part of an overall
sampling apparatus, being combined with the apparatuses
and methods of earlier embodiments to provide a uniform
cross-pipe GLR for sampling.

While the invention has been described in
conjunction with the exemplary embodiments described
above, many equivalent modifications and variations will
be apparent to those skilled in the art when given this
disclosure. Accordingly, the exemplary embodiments of
the invention set forth above are considered to be
illustrative and not limiting. Various changes to the
described embodiments may be made without departing from
the spirit and scope of the invention.